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13. ABSTRACT *(Maximum 200 words)*
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Research in Neural Network Based Adaptive Control

Final Report

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Principal investigator: Dr. Anthony J. Calise, Professor
Program Manager: Dr. Mark Q. Jacobs

RESEARCH IN NEURAL NETWORK BASED ADAPTIVE CONTROL

GRANT NUMBER: F49620-98-1-0437

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Objectives
The are two primary objectives of this research effort. The first is to develop theory and methodology for neural network based adaptive control of uncertain nonlinear systems. The second is to work closely with industry and government labs to achieve a rapid transition of our research results to problems of high value to the Air Force and to the aerospace industry.

Status of Effort
The most significant theoretical accomplishment has been the development of a new approach for dealing with control limits and nonlinearities in adaptive systems. This approach both prevents the adaptive system from doing harm to an otherwise stable system, and also allows adaptation to continue while the control is saturated. We regard this as a major step towards flight certification of adaptive controllers. The approach is more general in that it permits a broad class of input nonlinearities, including such effects as discrete and bang/bang control. In the area of output feedback, we continue to refine our earlier work, and have begun to take steps in the direction of decentralized adaptive systems in a state feedback setting. Our most significant interactions have been with NASA Marshall and NASA Ames. In particular, we are fully exploiting our research in limited authority adaptive control in the areas of autopilot design for launch vehicles, and propulsion control for commercial aircraft subject to partial or total loss of conventional flight control.

Accomplishments
Limited Authority Adaptive Control [12, 13]: A major improvement to our previous adaptive control work has been developed that addresses the following issues:

- Preventing adaptive windup due to input saturation (position and rate)
- Preventing adaptation to other known input dynamics
- Allowing adaptive control for mixed continuous and discrete controllers
- Enabling recovery from faulty adaptation
- Enabling "correct" adaptation while in partial or no control of the plant

The method has been termed Pseudo-Control Hedging (PCH). The purpose of the method is to prevent the adaptive element of an adaptive control system from trying to adapt to a class of system input characteristics. To do this, the adaptive law is prevented from "seeing" these characteristics. In this context, this means to prevent an adaptive

element, which in our work is a neural network (NN) from experiencing a system characteristic as model tracking error.

In order to illustrate some of the properties of an implementation of PCH, sample X-33 flight control system results will be described. For the failure case illustrated here, it is *temporarily not possible* to maintain reasonable model tracking. Near maximum dynamic pressure, half of the aerodynamic surfaces go hard-over in a pro-left turn (right rudder full trailing edge right, right elevons full trailing edge down, right body flap full trailing edge down). This is severe enough that insufficient control power remains to maintain the desired command until dynamic pressure drops. The vehicle does three rolls to the left before the dynamic pressure drops enough to stop the roll, attitude error angles shown in Figure 1. The control system utilizes no direct knowledge/measurement of the failure.

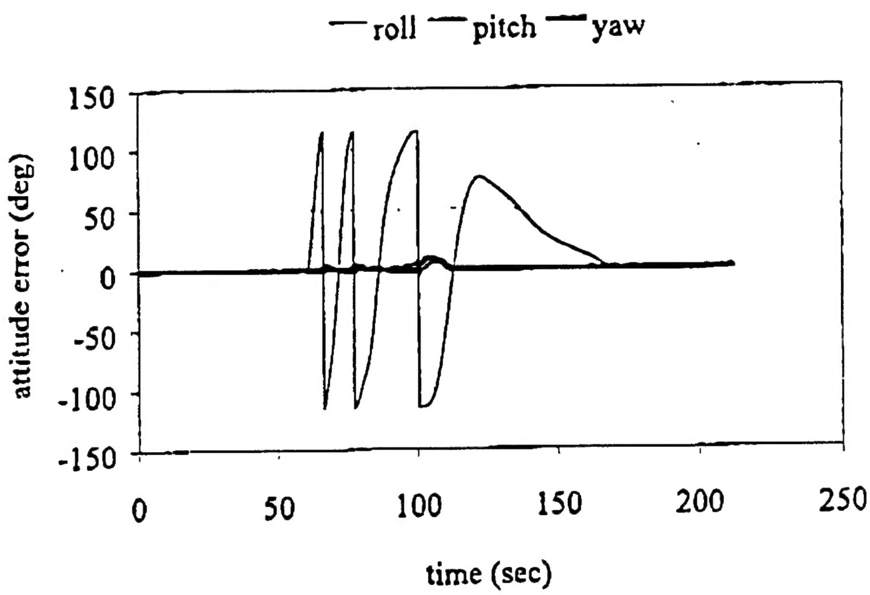


Figure 1 -- Attitude error angles for X-33 Ascent, multiple actuator hard-overs at 60 seconds, insufficient control power remains to maintain desired command for approximately 60 seconds

The remaining aerodynamic surface actuator commands are shown in Figure 2. During portions of this trajectory the remaining actuators are at absolute limits; in other portions they are experiencing axis priority limits. The model error and the adaptive signal (NN output) are shown in Figure 3. The adaptation signal tracks model error during the entire trajectory, i.e. the NN is well behaved in the presence of considerable actuator saturation.

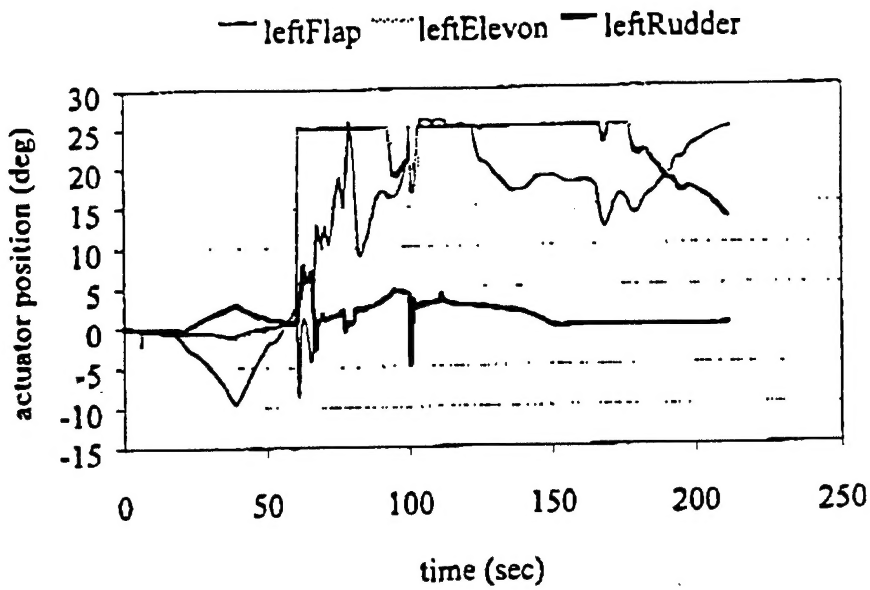


Figure 2 – Actual actuator positions for non-failed aerodynamic surface actuators

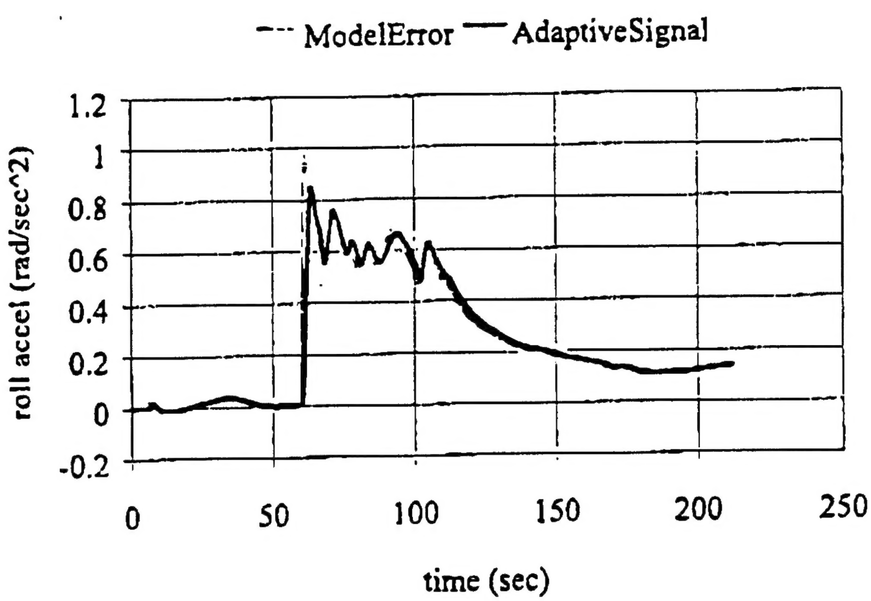


Figure 3 -- Roll model error and the adaptive signal; showing correct adaptation for multiple actuator hard-overs occurring at 60 seconds

Adaptive Bounding [15]:
Research in nonlinearly parametrized NNs, such as the single hidden layer (SHL) NNs, has been limited to conservative stability proofs that rely on the knowledge of an upper bound of the weight matrices. Specifically, in on-line adaptive SHL NN applications the most adopted update laws suffer from the need to choose the gains of a robustifying term. The purpose of this robustifying term is to guarantee stability by overbounding the neglected 2nd and higher order terms in the Taylor series expansion of the NN output. The

expansion is necessary in order to obtain implementable adaptive update laws. Experience has shown that this choice is not straightforward, as this term has the structure of a pure feedback term. Choosing a conservatively high gain causes a situation in which the adaptive NN signal does not appear to play any role.

A less conservative approach is to introduce an adaptive bound. By analyzing the higher order terms of the NN output, it is possible to derive a bound that is explicitly a function of known signals. The higher order terms can thus be overbounded by the product of an unknown gain and the known function. Boundedness of signals can be guaranteed by introducing an additional adaptive law that estimates the unknown gain. As a result, instead of having to guess the upper bound on the weight matrices and a feedback gain, it is necessary to choose the adaptation gain and the e-modification gain. This alternative approach is easier to implement, because in practice it is easier to adjust adaptation gains than guessing feedback gains and upper bounds to the ideal weights.

We have explicitly extended the use of the adaptive bound to Radial Basis Function (RBF) and SHL NNs. In RBF NNs the outer layer weights as well as the centers and widths of the neurons are adapted on-line.

Decentralized control design: We have developed adaptive decentralized state feedback control architecture for large-scale systems with interconnections being bounded by unknown nonlinear functions of tracking errors. The local subsystems are considered to be feedback linearizable. The learning rules for adaptive single hidden layer neural network controllers are backpropagation with e-modification, including adaptive bounding on the neglected higher order terms of the neural network Taylor series expansion, and on the interconnection functions. Sufficient conditions are derived for uniform ultimate boundedness of the tracking errors. Future research in this direction will attempt to extend these results to the output feedback case.

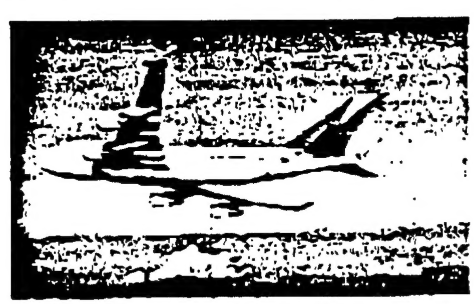
Personnel Supported

Faculty: Calise, A.J., Professor.
Visiting Scholar: Hovakimyan, N., Ph.D. in Physics and Mathematics from the Moscow Institute of Applied Mathematics.
Students: Nardi, F., graduate research assistant
Johnson, E., graduate research assistant

Interactions/Transitions

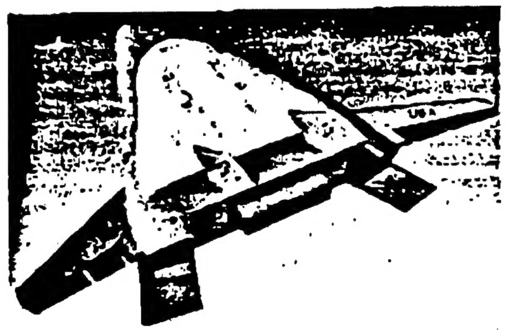
Conferences: ACC, AIAA GN&C, CDC (see reference list)

Civil Transportation [10]: We have a cooperative effort with NASA Ames in the area of flight safety. During this past year we delivered a NN based real time flight control system design, and integrated into their piloted simulation facility. It has undergone preliminary piloted evaluations. This approach uses a propulsion control mode to assist in controlling the aircraft when there is a failure in the primary flight control system. We are currently in



the process of incorporating our pseudo-control hedging approach to accommodate the control limits that are encountered in these applications.

__Launch Vehicles [12]:__ We are working with NASA Marshall to design an adaptive autopilot for the X-33 vehicle. This vehicle routinely flys with one or more of its actuators saturated over portions of its envelope. Also, the flight control system must accommodate a number of abort scenarios. Also, the actuation suite consists of a combination of both continuous control (variations in thrust magnitude) and discrete controllers (reaction control system). Therefore our adaptive design must allow for both position and rate saturation, and nonlinear controller effects due to the reaction control system. The existing design is gain scheduled with both flight condition and a family of abort scenarios. But all possible failures are not considered. Moreover the design is highly sensitive to changes in vehicle design, so that when a change is made, in many cases it is not possible to run the simulation without redesigning the gain tables. Our system has completely eliminated the need for gain tables. It makes no use of the aerodynamic data set, and out-performs the existing gain scheduled design. We have also successfully flown severe failure conditions in which the controls are saturated for long periods of time that the present flight control system can not tolerate. This is a natural application for our research in pseudo-control hedging, and we expect that in the future this effort will result in a major technology transition success.



Transitions

__Guided Munitions [11]:__ We are currently supporting a Phase-II SBIR effort with Guided Systems Technologies. This work is aimed at demonstrating that a single tail kit with a fixed autopilot design can be used to control a wide class of guided munitions. Also, the autopilot design must accommodate changes in mission profiles, without significant redesign. The design should not require accurate aerodynamic data as well. This will further reduce costs by reducing the need for wind tunnel testing. During this past year we have demonstrated that with our adaptive approach it is possible to design the autopilot using missile DATCOM data, without the benefit of wind tunnel data. Since we are using missiles from the existing inventory, for which accurate wind tunnel models exists, we were able to use the accurate models to demonstrate that envelope performance is equal to or better than the existing gain scheduled designs. A series of drop tests are planned for Phase-III.

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Honors/Awards

Naira Hovakimyan, Best Pesentation Aard for Session WM17-1 at the 2000 ACC.

Anthony Calise, AIAA Mechanics and Control of Flight Award, 1992.
AIAA Fellow, 1993.

Publications

1. Rysdyk, R.T., Calise, A.J., "Adaptive Model Inversion Flight Control for Tiltrotor Aircraft," AIAA J. of Guidance, Control, and Dynamics, (to appear).
2. Hovakimyan, N., Lee, H., and Calise, A. J., "On Approximate NN Realization of Unknown Dynamic Function from Input-Output History". Submitted to Automatica.
3. Calise, A. J., Hovakimyan, N., and Lee, H., "Adaptive Output Feedback Control of Nonlinear Systems using Neural Networks". Submitted to Automatica.
4. Hovakimyan, N., Rysdyk, R., and Calise, A. J., "Dynamic Neural Networks for Output Feedback Control". Accepted for publication in International Journal of Robust and Nonlinear Control.
5. Hovakimyan, N., Rysdyk, R., and Calise, A. J., "Dynamic Neural Networks for Output Feedback Control". 38th Conference on Decision and Control, Dec. 1999.
6. Giampiero, C., Sharma, M., and Calise, A. J., "Neural Network Augmentation of Linear Controllers with Application to Underwater Vehicles", American Control Conf., June 2000.
7. Hovakimyan, N., Lee, H., and Calise, A. J., "On Approximate NN Realization of an Unknown Dynamic System from its Input-Output History", American Control Conf., June 2000.
8. Calise, A. J., Hovakimyan, N., and Lee, H., "Adaptive Output Feedback Control of Nonlinear Systems using Neural Networks", American Control Conf., June 2000.
9. Calise, A. J., "Development of a Reconfigurable Flight Control Law for the X-36 Tailless Fighter Aircraft", AIAA Guidance, Navigation, and Control Conf., Aug. 2000.
10. Rysdyk, R., Leonhardt, B., and Calise, A. J., "Development of an Intelligent Flight Propulsion and Control Sytems: Nonlinear Adaptive Control", AIAA Guidance, Navigation, and Control Conf., Aug. 2000.
11. Sharma, M., Calise, A. J., and Corban, J. E., "Application of an Adaptive Autopilot Design to a Family of Guided Munitions", AIAA Guidance, Navigation, and Control Conf., Aug. 2000.
12. Johnson, E. N., Calise, A. J., Rysdyk, R., and El-Shirbiny, H., "Feedback Linearzation with Neural Network Augmentation Applied to X-33 Attitude Control", AIAA Guidance, Navigation, and Control Conf., Aug. 2000.
13. Calise, A. J., Lee. H., and Kim, N., "High Bandwidth Adaptive Flight Control", AIAA Guidance, Navigation, and Control Conf., Aug. 2000.
14. Sheikh, A., Prasad, J., and Calise, A. J., "Multilayer Neural Network and Adaptive Nonlinear Control of Turboshaft Engine", AIAA Guidance, Navigation, and Control Conf., Aug. 2000.
15. Nardi, F., Calise, A.J., "Robust Adaptive Nonlinear Control Using Single Hidden Layer Neural Networks", accepted to the 39th Conference on Decision and Control, Sydney, 2000.